PCOS Science with the X-ray Surveyor[1]

The NASA Astrophysics Roadmap "Enduring Quests, Daring Visions," envisions an X-ray Surveyor capable of answering fundamental questions about cosmic astrophysics. Here we highlight several of the scientific motives for X-ray Surveyor with particular relevance to the Physics of the Cosmos program: the origin of the first supermassive black holes; the physics of feedback linking black holes to the galaxies and clusters that surround them; the growth of cosmic structure and it influence on galaxy evolution; and physics at the extremes of strong gravity and super-nuclear density. As an observatory class mission, of course, X-ray surveyor will address a much broader range of astrophysics than we are able to mention here.

The Roadmap characterizes the X-ray Surveyor as an X-ray telescope with ~3 square meters of collecting area and sub-arcsecond angular resolution this is equipped with broad-band (0.1 – 10 keV) high-spectral-resolution (resolving power ~3000) focal plane instruments. [refer to the common table of missions]

The origin and growth of the first supermassive black holes. A driving science objective for X-ray Surveyor is to understand the origin and enigmatic growth of the first supermassive black holes, and to trace their co-evolution with their host galaxies. Black holes as large as 10^9 M_{sun} have evolved to be quasars by redshifts of 6 to 7, but have we do not know how objects so massive came to exist so early in cosmic history. Nor do we understand the nature and mass of the seed black holes from which these supermassive objects must have grown. X-Ray Surveyor will detect the central black holes in the earliest galaxies detected by JWST at redshifts of ten and higher. It will reveal the physical processes by which these objects have grown by observing black holes in their youth, with sufficient sensitivity to detect seed black holes as small as 10^4 M_{sun} at z=10 (under the reasonable assumptions of Eddington-limited accretion, with 10% of bolometric luminosity in the hard band). More massive seeds will be detected even earlier in cosmic time. X-rays are optimal probes of these high-redshift, moderate-mass ($M < 10^6$ M_{sun}) seed black holes because the spectral peak of their emission shifts with decreasing mass to wavelengths shortward of the UV, because X-rays can penetrate the host-galaxy dust that would obscure UV and optical emission, and because the IR signatures of AGN activity are red-shifted out of the JWST band. This scientific objective is a key driver of X-Ray Surveyor's angular resolution, which is crucial to its capability to study these faint objects. X-ray Surveyor's source detection flux limit is almost 100 times fainter than Athena's, as the latter is limited by source confusion (see Figure 1).

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[1] Much of this section has been adapted from a white paper by Jessica Gaskin, Alexey Vikhlinin, Martin Weisskopf and Harvey Tannenbaum. Steve Allen, Laura Brenneman, Deepto Chakrabarty, John Nousek and Mike Nowak also provided valuable input. Material was also adapted from the NASA Astrophysics Visionary Roadmap.

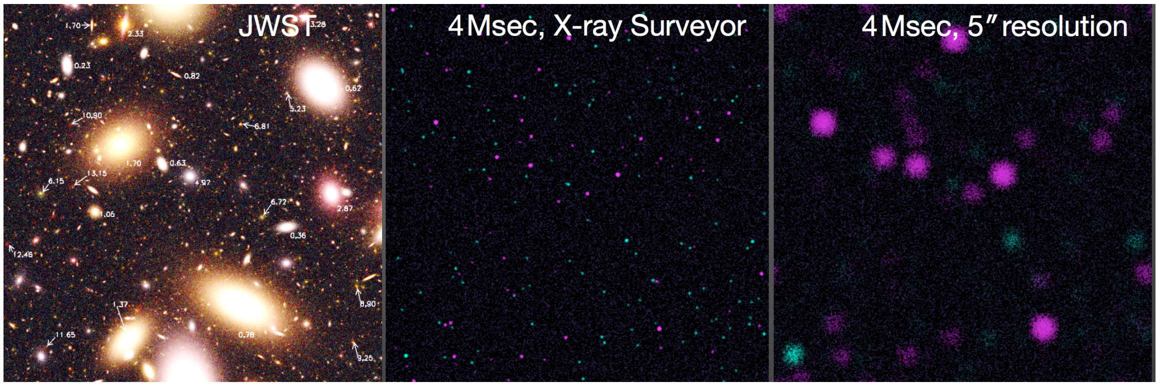

Figure 1 Simulated Deep Fields with JWST (left) and X-ray Surveyor (Center). Each is 2 arcmin on side. JWST detects ~ 2 x 10^6 galaxies deg^{-2}. X-ray Surveyor resolves these without confusion (0.03 galaxies per 0.5" beam). A 4 Ms X-ray Survyor exposure (same as the Chandra Deep Field) detects a 10^4 M_{sun} black hole at z=10 (Lx 10^{41} erg s^{-1}). A telescope with the same area but 5" resolution (right) is confusion limited at this depth. AGN are shown in magenta; normal galaxies in green. [Gaskin, Vikhlinin et al.]

X-ray Surveyor will also probe the host galaxies of the $M\sim 10^9$ M_{sun} black holes powering z~6 Sloan quasars. These must be the largest galaxies, and hence reside in the largest dark matter halos ($M \sim 10^{12}$ M_{sun}) to have evolved by that epoch. The expected diffuse X-ray emission from one of these galaxies has only a small fraction of the quasar's luminosity, and X-ray Surveyor's angular resolution is necessary to separate quasar from halo emission, enabling measurement of the gas temperature and thereby halo mass.

The Physics of Feedback and Accretion in Galaxies and Clusters. X-ray Surveyor is also driven by the need to understand the physics of galaxy assembly at more recent epochs. In Milky-Way sized galaxies, models predict that a substantial fraction (as much as 1/3) of the baryons reside in hot ($T \gtrsim 10^6$ K) gas extending far beyond the stellar component. These hot haloes must play a significant role in, and contain quantitative information about, the feedback processes that balance gravity and cooling to regulate gas accretion and, ultimately, star formation as galaxies evolve. At present our observational knowledge of these hot components is limited to a few nearby objects. X-ray Surveyor will characterize the quantity, composition and energy content of the hot gas in Milky-Way sized halos out to $z \sim 1$. Its angular resolution is crucial to its capability to map this emission while clearly resolving it from central AGN and unrelated background and foreground sources.

In the immediate vicinity of the AGN, high-resolution, time-resolved soft X-ray grating spectra of will measure mass outflow rates in winds, providing quantitative information about the matter and energy injected by supermassive black holes into their host galaxies. These same data will also illuminate the physics of supermassive black hole accretion and jet formation, collimation and reacceleration; we return to this point below.

At the largest scales, X-ray Surveyor's spectral maps of galaxy cluster plasma, with an unprecedented combination of spatial and spectral resolution, will reveal the kinematics and characterize the physical mechanisms responsible for the bubbles, ripples, and fronts detected by Chandra. These maps will measure turbulent heating, trace radiative cooling and matter flows, and constrain plasma transport properties, providing a quantitative physical understanding of the enormous feedback loops that operate over ten orders of magnitude in length scale in clusters.

Galaxy Evolution and the Growth of Cosmic Structure: Just as galaxies co-evolve with the black holes they host, so also are they shaped by the growing cosmic structures enveloping them. With the formation of galaxy groups, galaxies experience more frequent mergers, and they interact via ram pressure with the hot, intragroup medium. These processes in turn induce nuclear activity and modulate star formation. X-ray Surveyor will detect groups at redshifts as large as z~4, and, crucially, will resolve AGN from the extended intragroup medium. It will also detect and distinguish the thermal emission of intragroup plasma from (non-thermal) inverse Compton X-ray emission from radio jets. X-ray Surveyor will track the evolution of these systems through the peak of cosmic star formation to the present epoch, providing new understanding of the physics linking the histories of black holes, galaxies and cosmic structure.

X-ray Surveyor will also reveal and study a substantial fraction of the as-yet unobserved, un-virialized baryons in the local Universe, and in so doing trace the cosmic web of dark and baryonic matter linking galaxies, groups and clusters. Models predict that as much as half of the hot baryons in the cosmic web will be detectable in emission at X-ray Surveyor's surface brightness limit (about 1/30 that of Chandra's) in the 0.5-2 keV band even in the absence of significant metal enrichment. These images will trace density enhancements as low as $\rho_{web}/\rho_{mean} = 30$. If the web is enriched to the extent expected from simulations and suggested by currently available observations in cluster outskirts, X-ray Surveyor's high-resolution grating spectroscopy will reveal it in absorption spectra along many sightlines to background sources. These spectra will illuminate the history and physics of the web's baryons by diagnosing their composition, ionization state, temperature and kinematics.

Extreme Environments: X-ray emission from both supermassive and stellar-mass black holes encodes the complex behavior of matter and the character of the spacetime in the immediate vicinity of the event horizon. Temporal variability reveals the timescales of turbulence and instabilities in the accreting matter, while the X-ray spectrum diagnoses its temperature, density, and kinematics, as well as the gravitational potential in which it is embedded. This information can be exploited, for example, to measure a black hole's angular momentum, which, along with its mass, completely characterizes an astrophysical black hole. The distribution of 'spin' in the supermassive black hole population is a powerful diagnostic of the relative importance of mergers and accretion in the recent growth of these objects. Moreover, spin plays a fundamental role, not yet understood, in the production of jets, which, in turn, link in the evolution of central black holes and their host galaxies. X-ray Surveyor's large collecting area and high spectra resolving power, supplemented by a modest hard X-ray instrument, will enable spin measurements of many more objects, over a much broader range of black hole mass and distances, than the few dozen that have so far been studied by Chandra, XMM-Newton and NuSTAR.

Another extreme, that of the super-nuclear density of matter in neutron stars, is also accessible through sensitive, time-resolved X-ray spectroscopy. Nowhere else in the cosmos do we encounter such high densities (approaching 10^{27} gm cm^{-3}), and the state of matter under these conditions is unknown. Different physical models, some invoking exotic forms, predict different pressure-density relationships, and these may in principle be distinguished by measuring the run of neutron star radius with mass. A measurement of neutron star radius accurate to 10%, at a given mass, for example, would distinguish a core composed of nucleons from one made of quarks. While the masses of neutron stars can be established with some precision, their radii are much more difficult to determine. X-ray emission from the hot matter on the neutron star surface is sensitive to radius, however, and high-quality data from X-ray Surveyor promise definitive new understanding of the nature of matter in neutron star interiors. For example, measurement of weak absorption features imprinted by the thin neutron star atmosphere will yield the gravitational redshift and mass:radius ratio; Doppler broadening from the surface rotation, together with the rotation period, yields the radius. Alternatively, the energy-dependence of the amplitude and detailed shapes of X-ray pulse profiles, which is affected gravitational light-bending near the surface, may be used to infer radius. X-ray Surveyor's large collecting area and high spectral resolution will make these measurements possible.